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F02K 1/72; F02K 1/805

See application file for complete search history.

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 895 days.

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(51) **Int. Cl.**

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F02K 1/80 (2006.01)

F02C 7/28 (2006.01)

(52) U.S. Cl.

CPC ... ***F02K 1/09*** (2013.01); ***F02C 7/28*** (2013.01);
F02K 1/805 (2013.01); ***F05D 2240/55***
(2013.01); ***Y02T 50/672*** (2013.01)

(57) **ABSTRACT**

A primary seal assembly for a variable area fan nozzle (VAFN) equipped turbofan engine includes a deformable seal and a seal retainer attached to the seal. The seal includes an inner wall and webs attached to the inner wall and extending transversely therefrom. The inner wall and the webs extend circumferentially at least partially around a bypass duct of the turbofan engine. An inner surface of the inner wall interfaces with the VAFN when the VAFN is in the stowed position. The seal is compressed between the VAFN and the seal retainer when the VAFN is in the stowed position. And each of the webs is deformed into a non-planar configuration when the VAFN is in the stowed position.

(58) **Field of Classification Search**

CPC F02C 7/28; F05D 2240/55; F02K 1/09;
F02K 1/1238; F02K 1/1246; F02K 1/1253;

20 Claims, 13 Drawing Sheets

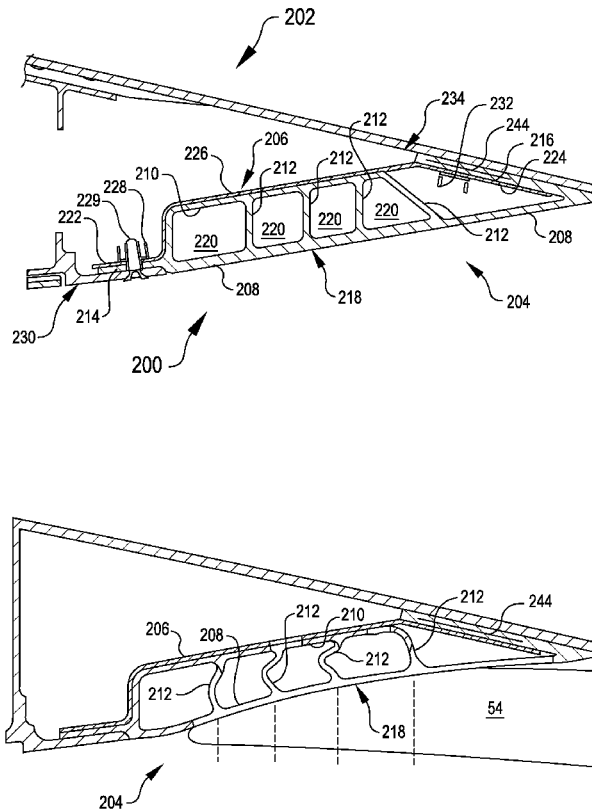


FIG. 1

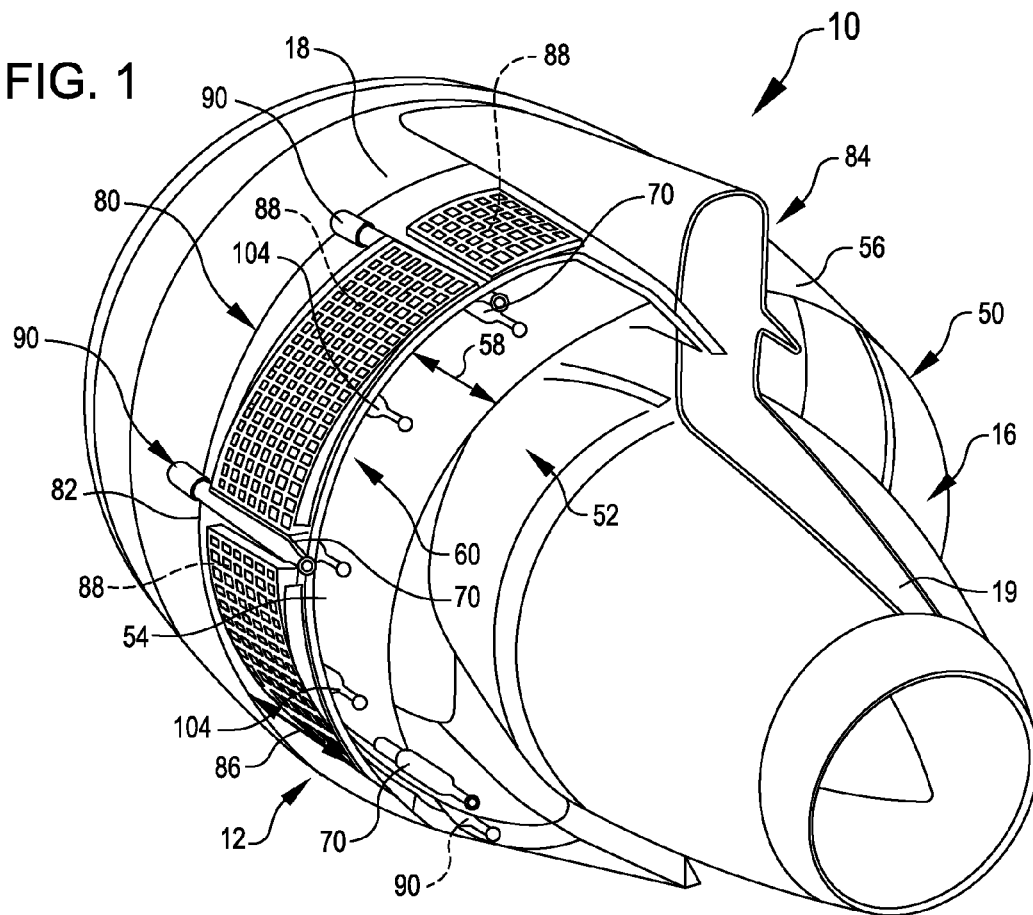


FIG. 2

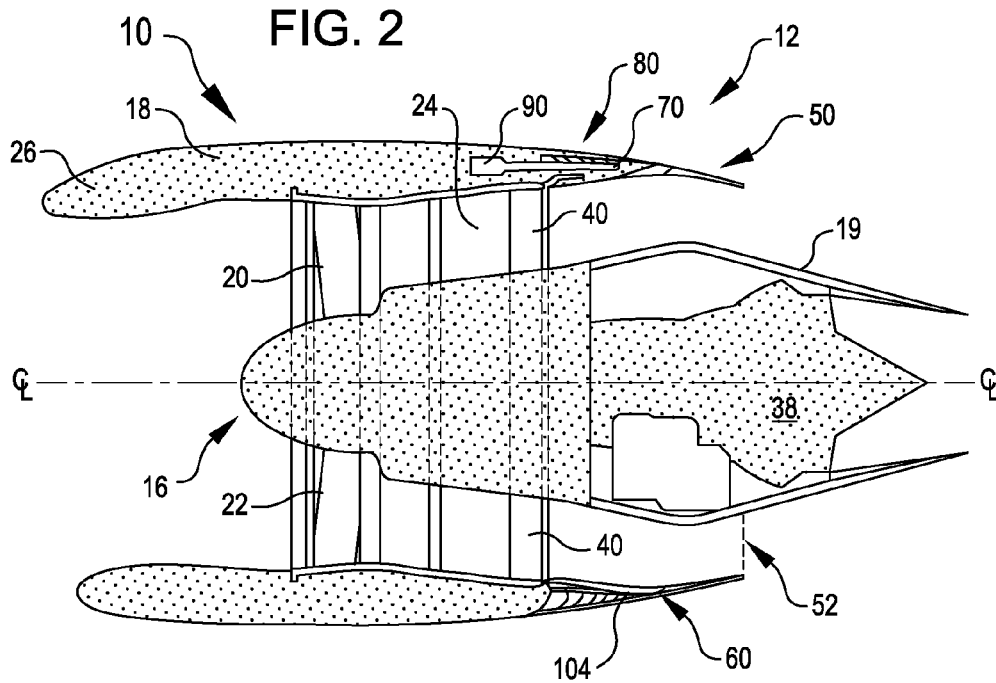


FIG. 3

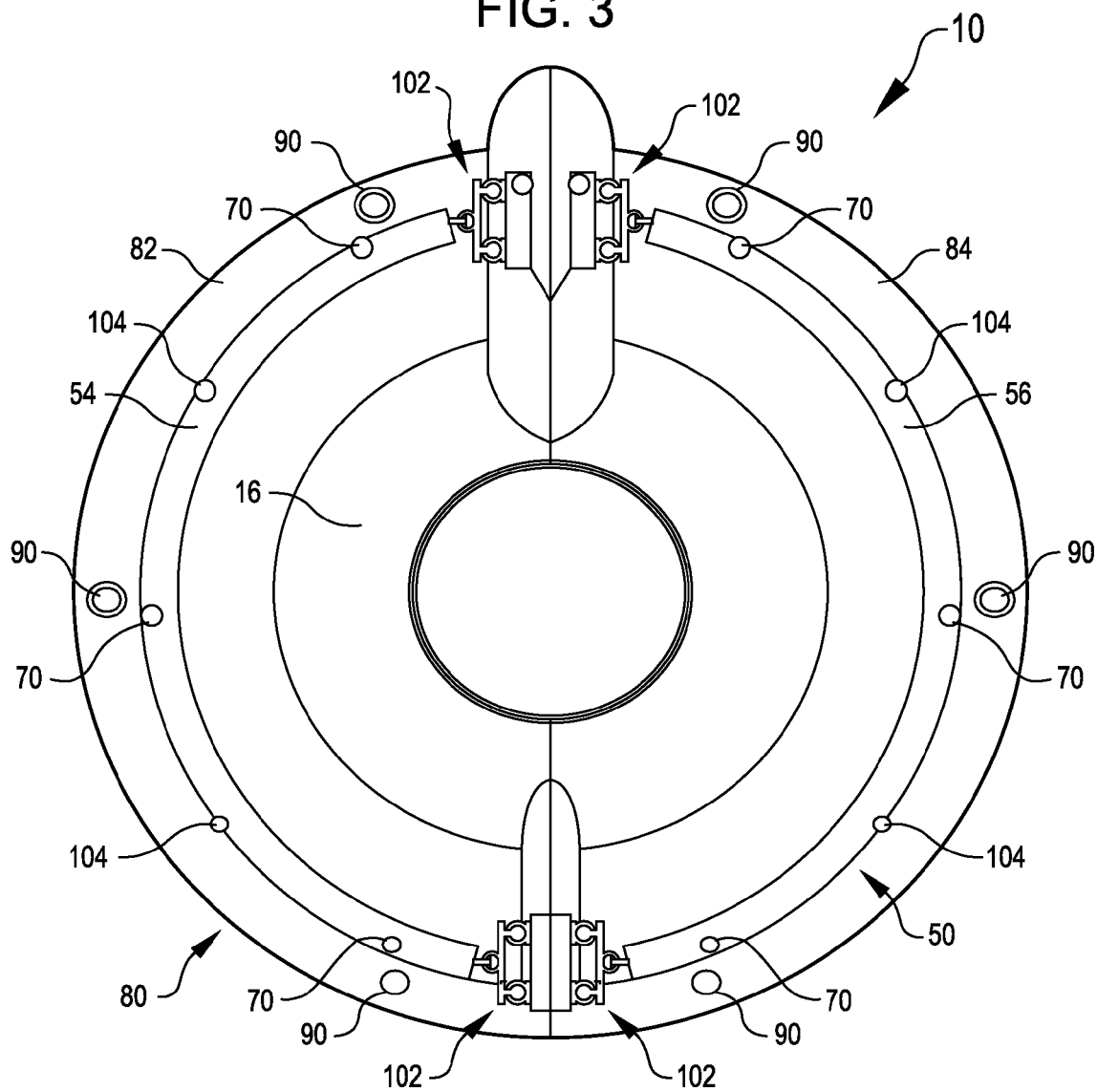


FIG. 4

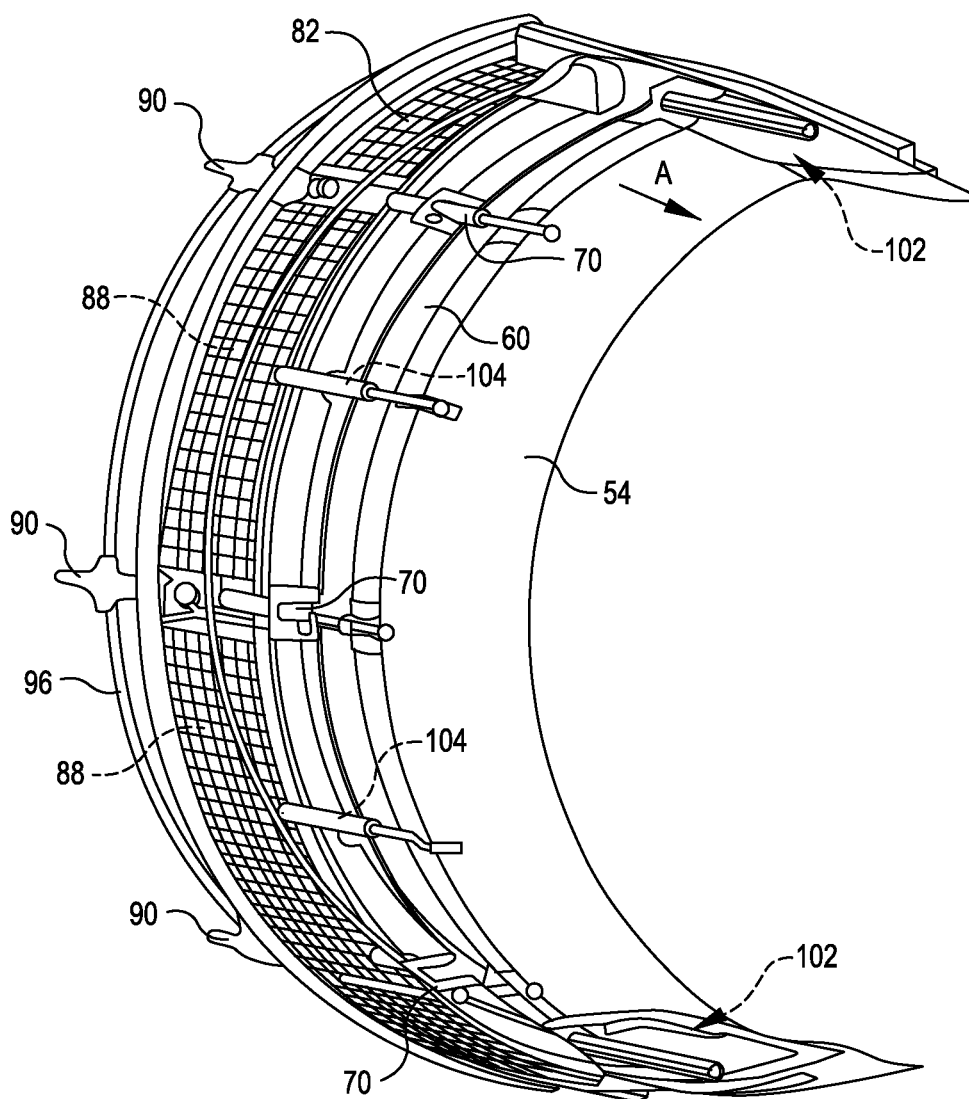
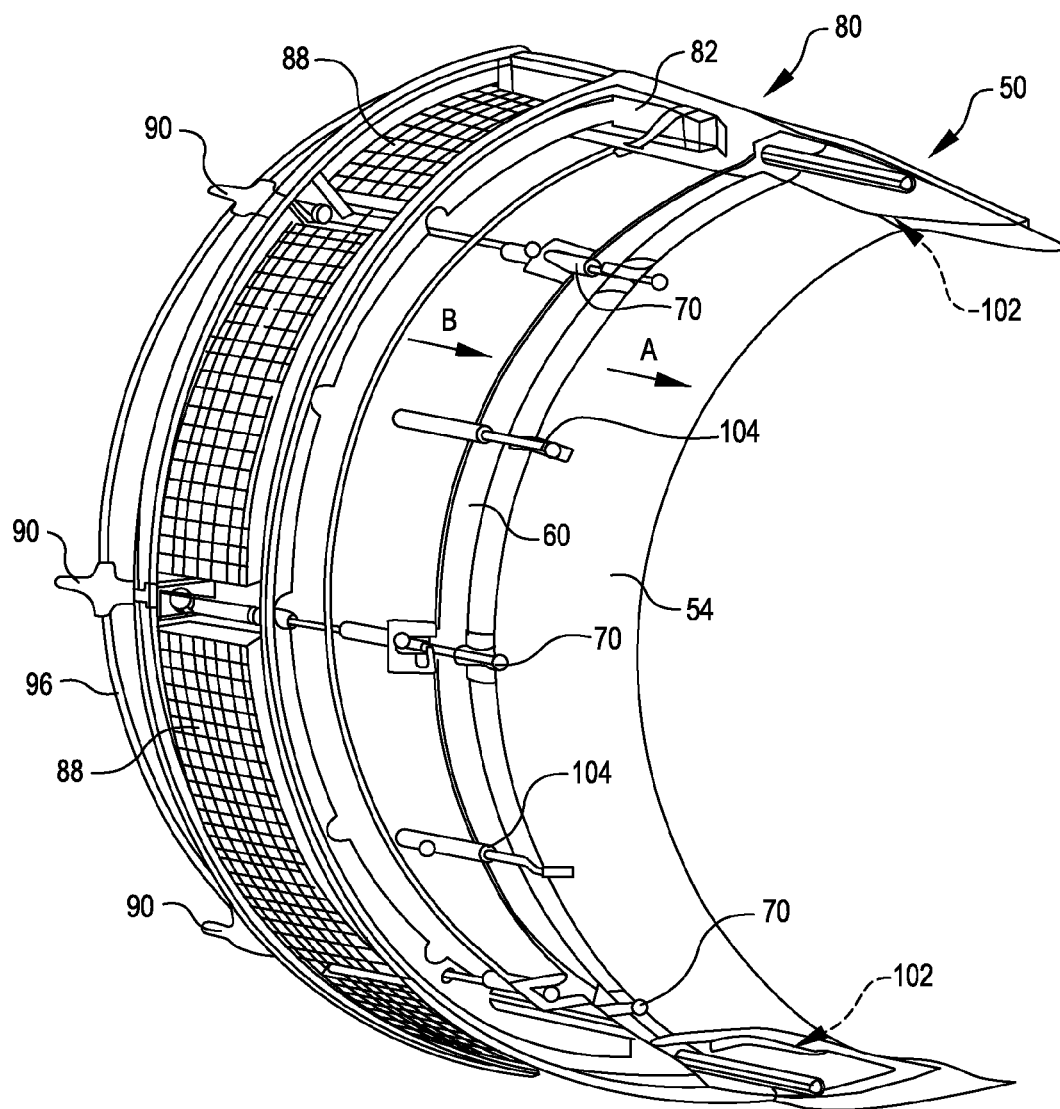
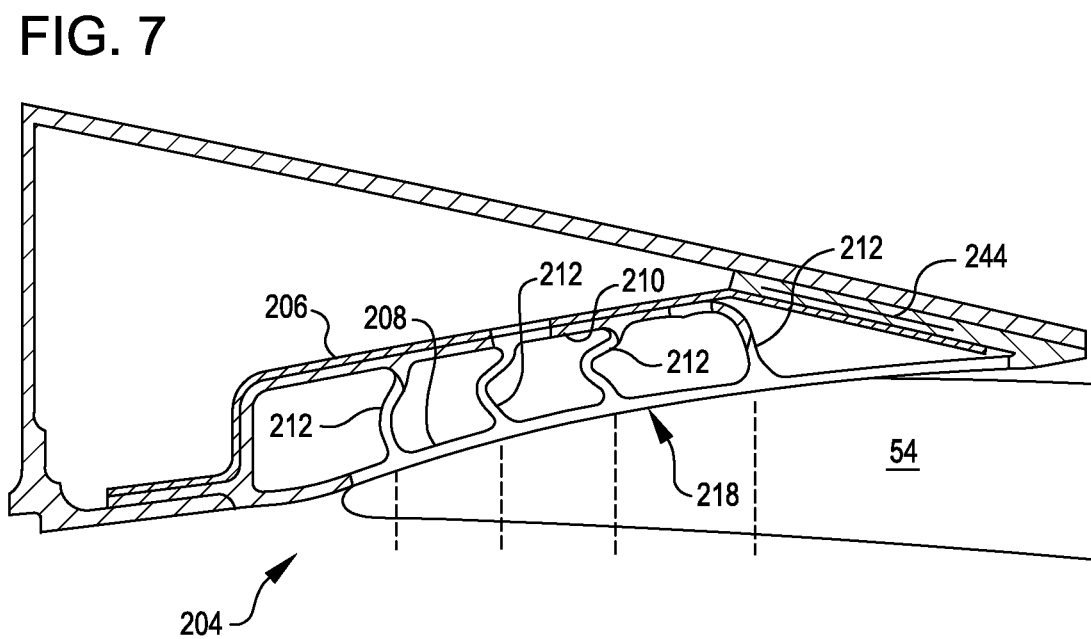
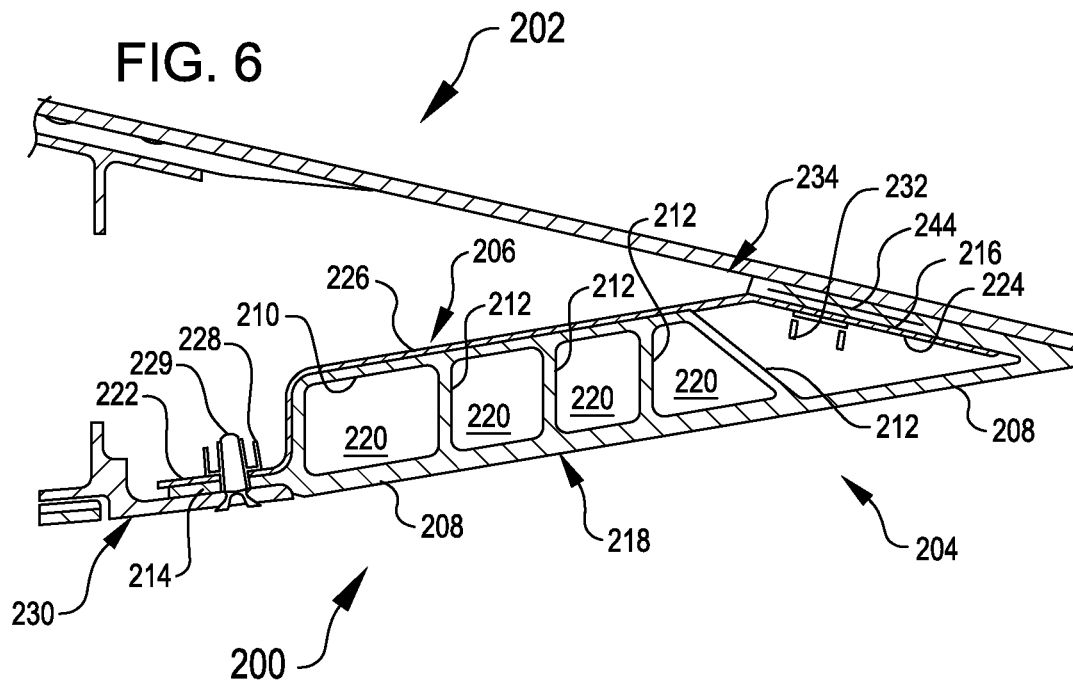


FIG. 5





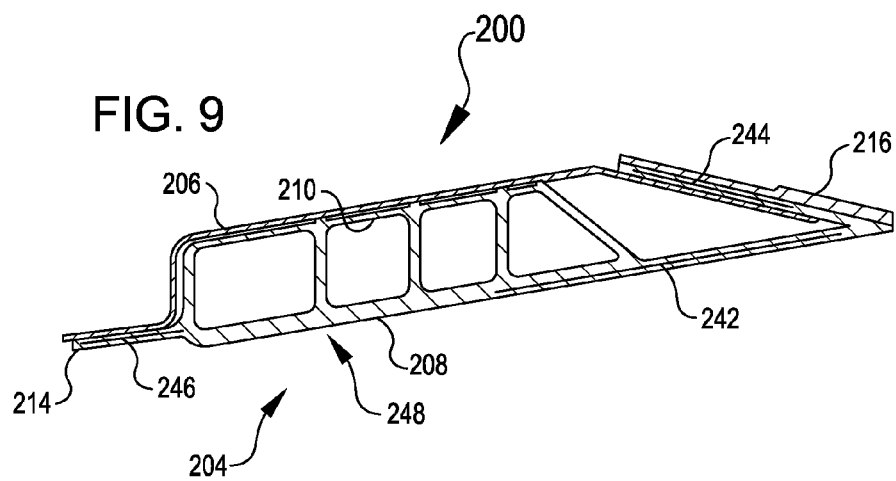
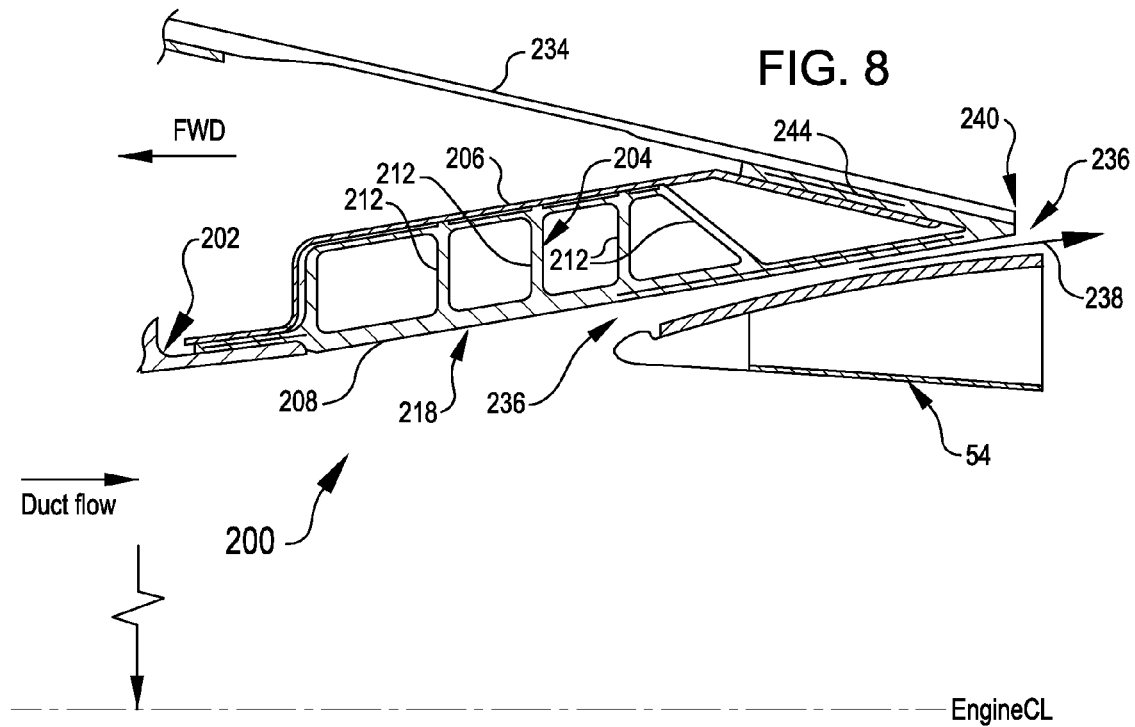


FIG. 10

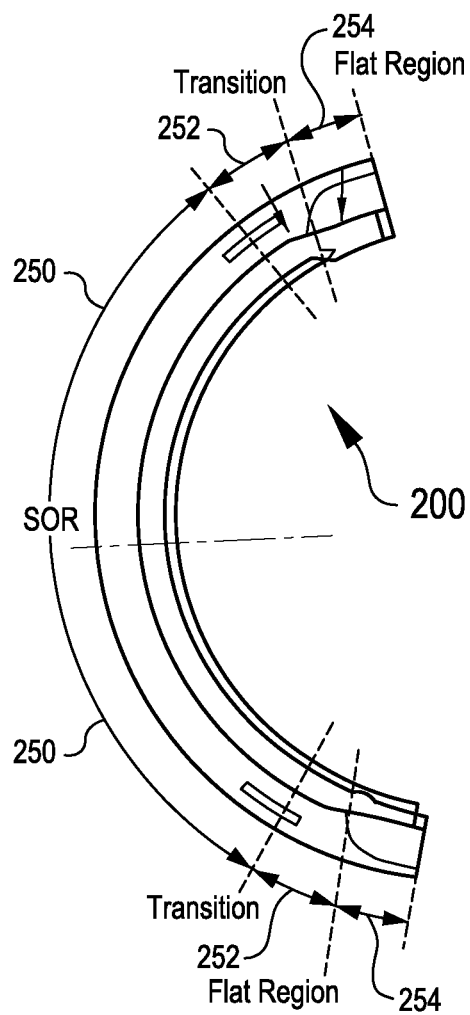


FIG. 11

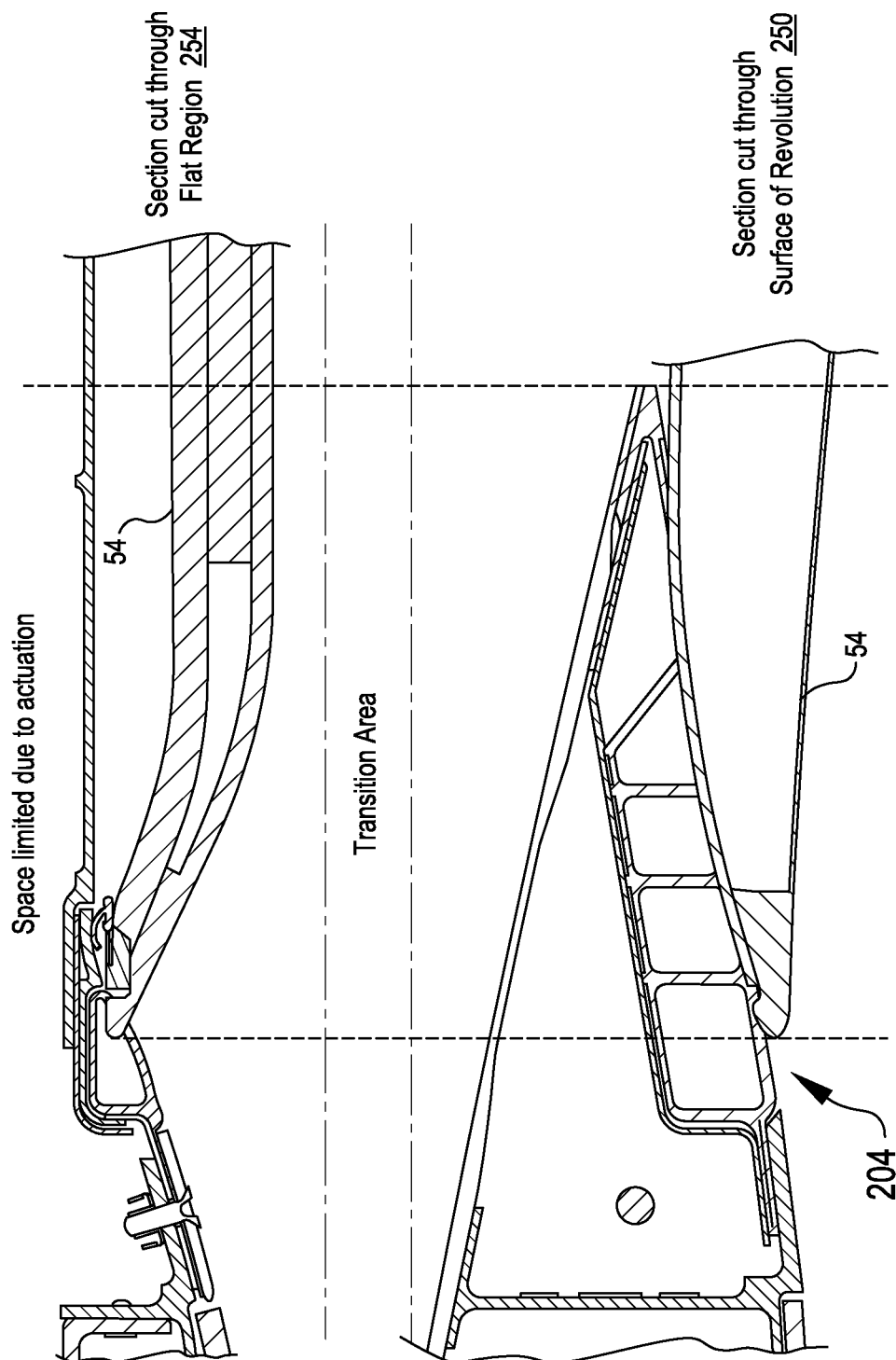


FIG. 12

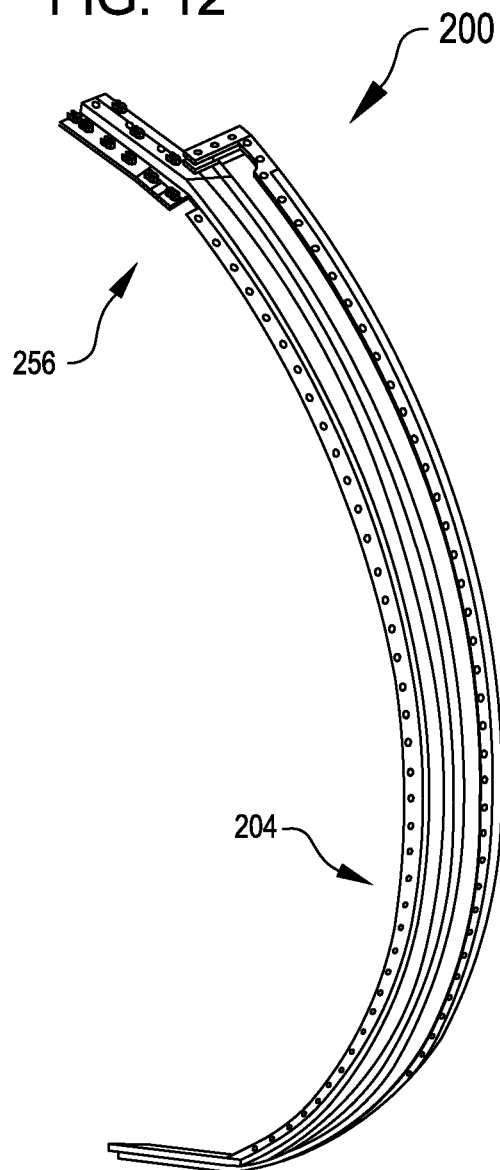


FIG. 13a

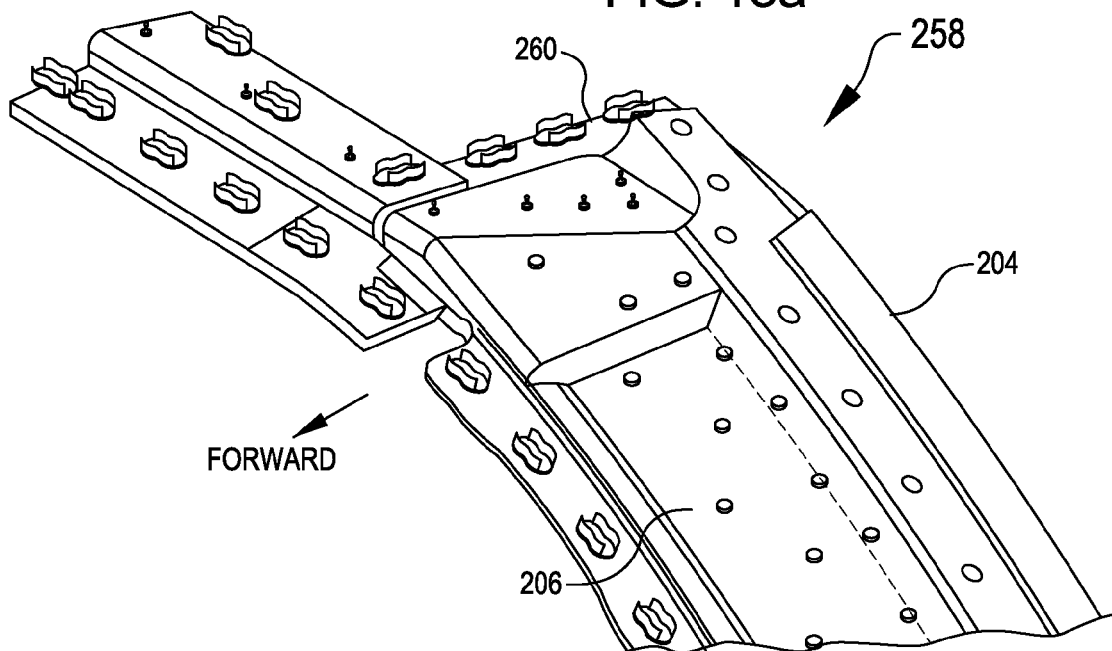


FIG. 13b

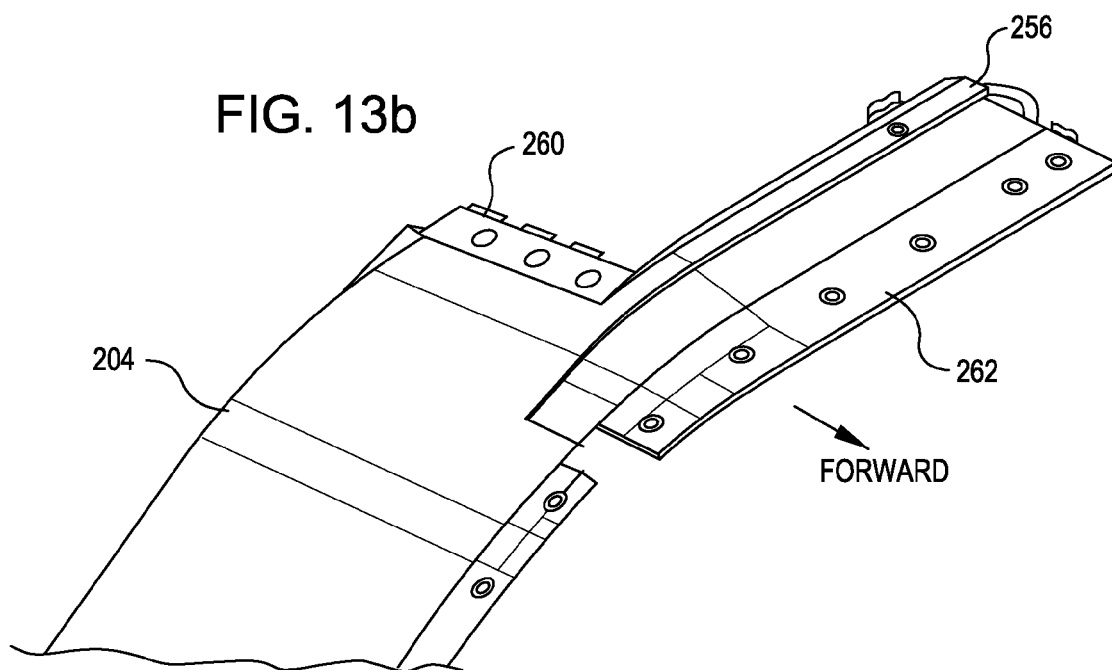


FIG. 14

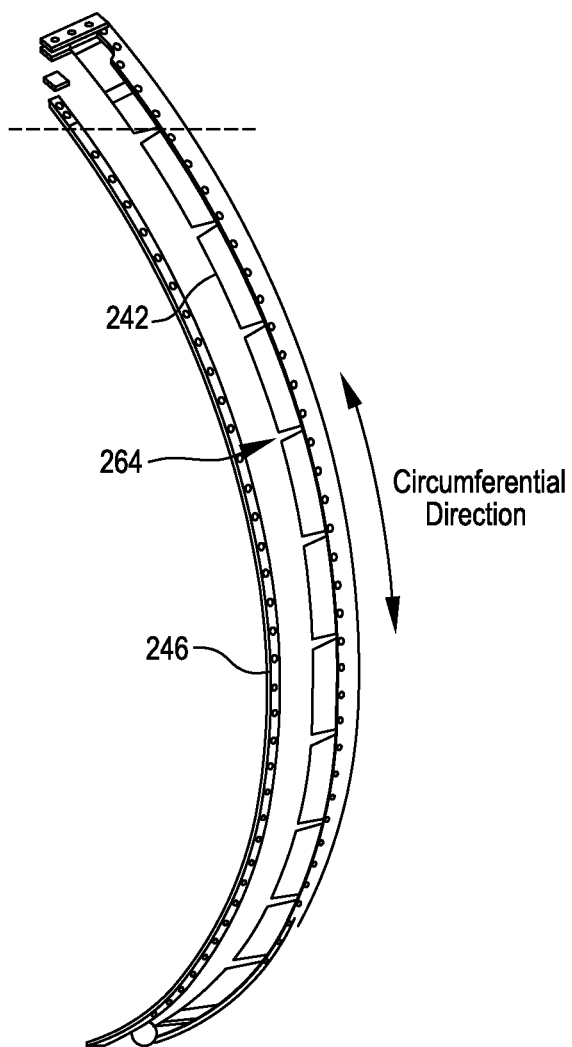


FIG. 15

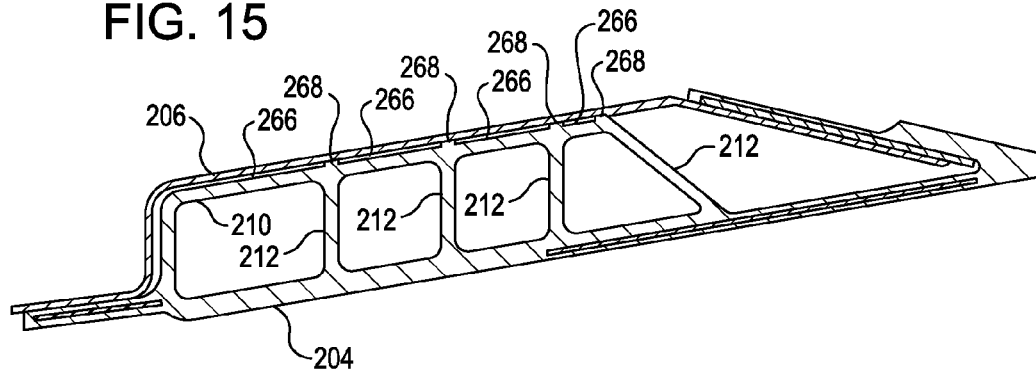


FIG. 16a

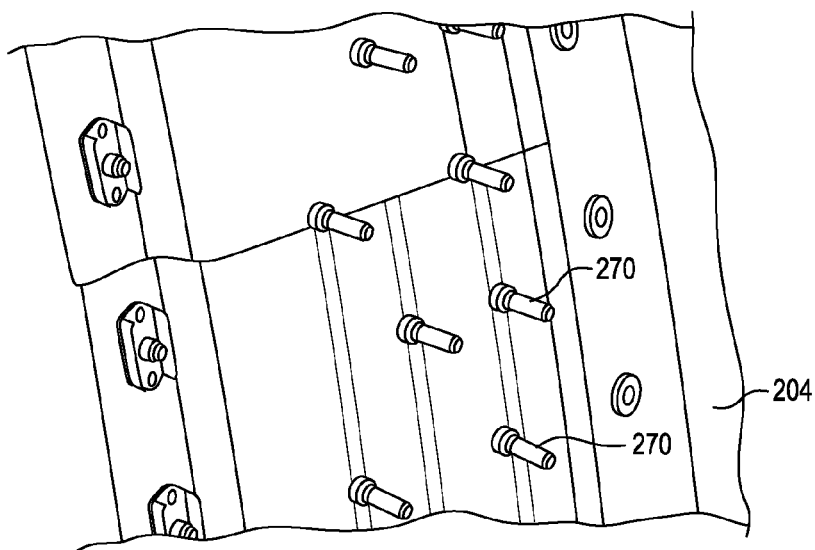


FIG. 16b

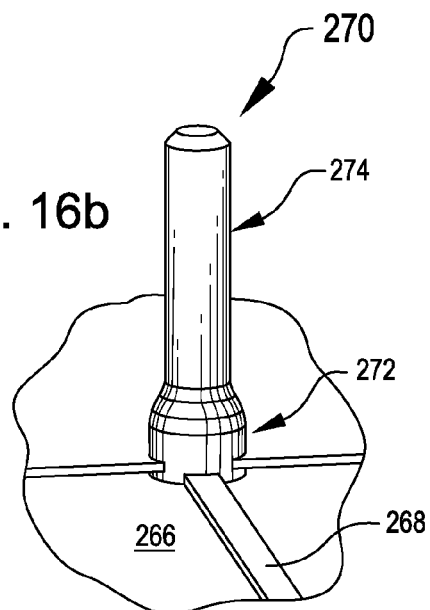
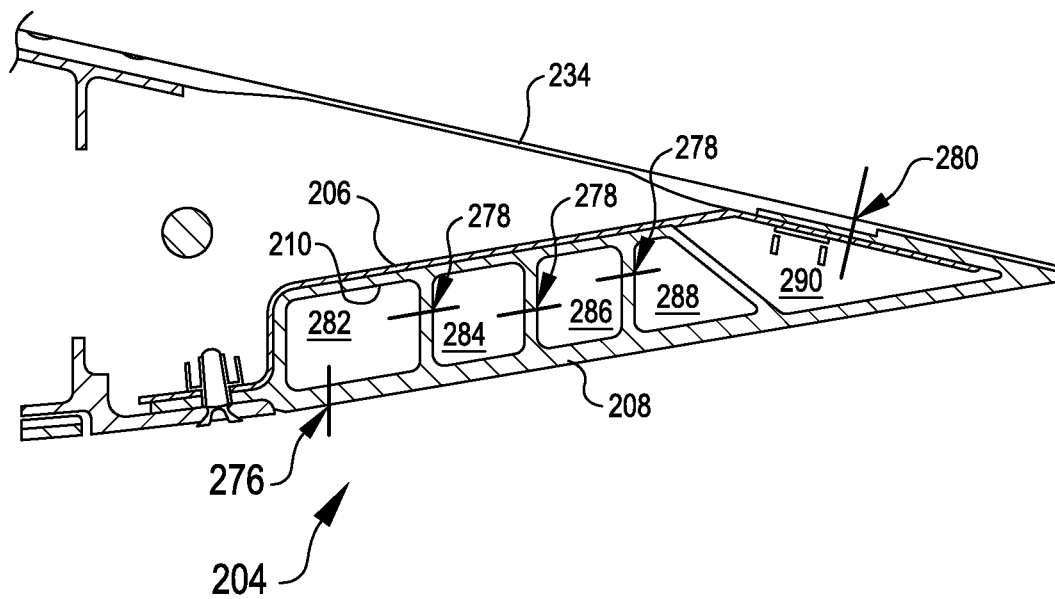


FIG. 17



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SEAL FOR A VARIABLE AREA FAN NOZZLE

BACKGROUND

Typical aircraft turbofan jet engines include an engine core, a nacelle that surrounds the engine core, and a fan that draws in a flow of air that is split into bypass airflow and engine core airflow. The nacelle provides a bypass duct that surrounds the engine core. The bypass airflow is transported through the bypass duct. The nacelle is configured to promote laminar flow of air through the bypass duct. The engine core includes a multi-stage compressor to compress the engine core airflow, a combustor to add thermal energy to the compressed engine core airflow, and a turbine section downstream of the combustor to produce mechanical power from the engine core airflow. The typical turbine section has two and sometimes three turbine stages. The turbine stages are used to drive the compressor and the fan. After exiting from the turbine section, the engine core airflow exits through an exhaust nozzle at the aft end of the engine.

In a turbofan engine, the fan typically produces a majority of the thrust produced by the engine. The bypass airflow can be used to produce reverse thrust typically used during landing. Thrust reversers mounted in the nacelle selectively reverse the direction of the bypass airflow to generate reverse thrust. During normal engine operation, the bypass airflow may or may not be mixed with the exhausted engine core airflow prior to exiting the engine assembly.

Several turbofan engine parameters have a significant impact upon engine performance. Bypass ratio (BPR) is the ratio of the bypass airflow rate to the engine core airflow rate. A high BPR engine (e.g., BPR of 5 or more) typically has better specific fuel consumption (SFC) and is typically quieter than a low BPR engine of equal thrust. In general, a higher BPR results in lower average exhaust velocities and less jet noise at a specific thrust. A turbofan engine's performance is also affected by the engine's fan pressure ratio (FPR). FPR is the ratio of the air pressure at the engine's fan nozzle exit to the pressure of the air entering the fan. A lower FPR results in lower exhaust velocity and higher propulsive efficiency. Reducing an engine's FPR can reach a practical limit, however, as a low FPR may not generate sufficient thrust and may cause engine fan stall, blade flutter, and/or compressor surge under certain operating conditions.

One approach for optimizing the performance of an engine over various flight conditions involves varying the fan nozzle exit area. By selectively varying the fan nozzle's exit area, an engine's bypass flow characteristics can be adjusted to better match a particular flight condition, for example, by optimizing the FPR relative to the particular thrust level being employed. For example, a variable area fan nozzle (VAFN) that forms a rear outer portion of the bypass duct can be moved aft so as to open an additional bypass flow exit forward of the VAFN. The VAFN can be selectively positioned anywhere between a stowed position in which no additional bypass exit is formed and a fully deployed position in which the additional bypass exit is open to a maximum extent.

Integrating a VAFN into an engine nacelle, however, presents challenges that arise from conflicting goals. In the stowed position, it is preferable that the VAFN interfaces with the rest of the nacelle such that the additional bypass exit is closed and sealed without inducing high stowing related loads in actuators used to position the VAFN. Accordingly, to meet stowed position sealing goals, it is desirable to have interfacing components with low stiffness. In the deployed position, however, it is preferable that the resulting additional bypass exit has desirable aerodynamic characteristics, such as low

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drag. Accordingly, to meet deployed position aerodynamic goals, it is desirable that the foregoing interfacing components be sufficiently stiff to avoid undesirable deflections, which can cause aerodynamic drag.

Accordingly, improved interfacing components for a VAFN are desired, such as a primary seal assembly having good stowed and deployed position characteristics.

BRIEF SUMMARY

The following presents a simplified summary of some embodiments of the invention in order to provide a basic understanding of the invention. This summary is not an extensive overview of the invention. It is not intended to identify key/critical elements of the invention or to delineate the scope of the invention. Its sole purpose is to present some embodiments of the invention in a simplified form as a prelude to the more detailed description that is presented later.

Primary seal assemblies for variable area fan nozzle (VAFN) equipped turbofan engines are disclosed. And turbofan engines equipped with a VAFN and associated VAFN primary seal assembly are disclosed. The disclosed primary seal assemblies employ a seal having webs that are deformable into a non-planar configuration when the VAFN is in the stowed configuration, thereby providing stowed position sealing without inducing large actuator stowing loads. The seal is also configured to avoid excessive deployed position deflections, thereby avoiding associated increases in aerodynamic drag. And a lightweight seal retainer is disclosed that, when attached to the nacelle assembly forward of the VAFN, positions the seal accurately and reacts loads from the seal to the nacelle forward assembly. In addition to having good durability, the disclosed seal assemblies are easily removed and replaced if necessary.

Thus, in one aspect, a nacelle is provided for a turbofan engine having an engine centerline. The nacelle includes a forward assembly, a variable area fan nozzle (VAFN) disposed behind the forward assembly, and a seal attached to the forward assembly. The forward assembly defines a bypass duct that extends circumferentially at least partially around the engine centerline. The bypass duct is configured to transport bypass airflow of the engine. The forward assembly has an aft edge that extends circumferentially at least partially around the bypass duct. The VAFN is movable relative to the forward assembly between a stowed position and a deployed position. An upstream bypass flow exit for the bypass duct is defined between the forward assembly and the VAFN when the VAFN is in the deployed position. An outer surface of the VAFN provides an aerodynamic boundary for bypass airflow exited through the bypass flow exit. The seal includes an inner wall and a plurality of webs attached to the inner wall and extending transversely therefrom. Each of the webs extends circumferentially at least partially around the bypass duct. The inner wall defines an exposed inner surface that extends circumferentially at least partially around the bypass duct. The inner surface provides a substantially smooth aerodynamic boundary for bypass airflow exited through the bypass flow exit when the VAFN is in the deployed position. At least a portion of the inner surface interfaces with the VAFN outer surface when the VAFN is in the stowed position so as to seal the bypass flow exit. Each of the webs has a non-planar configuration when the VAFN is in the stowed position.

The seal can be configured to circumferentially extend around the engine centerline to a significant extent. For example, the seal can extend circumferentially around the engine centerline for at least 90 degrees.

The seal can be adapted in accordance with the geometry of the forward assembly and the VAFN. For example, a height of the seal can be tapered down near an end of the seal.

The nacelle can include additional seals suitable for the geometry of the forward assembly and the VAFN. For example, the nacelle can further include a bulb seal attached to the forward assembly and disposed near the end of the seal. The bulb seal is compressed between the forward assembly and the VAFN when the VAFN is in the stowed position.

In many embodiments, each of the webs has a planar configuration when the VAFN is in the deployed position. The planar web configuration serves to provide solid support for the inner wall so that the inner wall deflections are minimized, and in any event are acceptable from an aerodynamic perspective.

In many embodiments, the seal includes an elastomeric material. For example, the elastomeric material can include any suitable resiliently deformable material, such as silicon rubber.

The seal can include any suitable number of webs. And any suitable subset of the webs can be configured to be resiliently deformed into a non-planar configuration when the VAFN is in the stowed position. For example, the plurality of webs can include three webs. Any suitable subset of the three webs (e.g., one, two, three) can be resiliently deformed into a non-planar configuration when the VAFN is in the stowed position. And any suitable subset of the three webs (e.g., one, two, three) can have a planar configuration when the VAFN is in the deployed position. As another example, the plurality of webs can include four webs. Any suitable subset of the four webs (e.g., one, two, three, four) can be resiliently deformed into a non-planar configuration when the VAFN is in the stowed position. And any suitable subset of the four webs (e.g., one, two, three, four) can have a planar configuration when the VAFN is in the deployed position.

In many embodiments, the nacelle further includes a seal retainer that defines a seal receiving cavity for the seal. The seal receiving cavity has an arcuate shape extending circumferentially at least partially around the bypass duct. The seal retainer includes a retainer forward flange, a retainer aft flange, and a retainer middle portion extending between the retainer forward and aft flanges. Each of the retainer forward and aft flanges extends circumferentially at least partially around the bypass duct and is attached to the nacelle forward assembly. The seal is located between the VAFN and the retainer middle portion when the VAFN is in the stowed position. The seal can include a seal forward flange that extends circumferentially at least partially around the bypass duct and a seal aft flange that extends circumferentially at least partially around the bypass duct. The seal forward flange can be disposed between the retainer forward flange and the forward assembly. And the seal aft flange can be disposed between the retainer aft flange and the forward assembly. At least one of the seal forward flange or the seal aft flange can include an embedded layer to serve as an internal reinforcement with respect to attachment fastener load transfer.

In many embodiments, the seal includes an outer wall offset from the inner wall and attached to the webs so that a plurality of enclosed cell areas is defined within the seal. The enclosed cell areas extend circumferentially at least partially around the bypass duct. The outer wall can be attached to any suitable support, such as the retainer middle portion or a support provided by the nacelle forward assembly. For example, the outer wall can be bonded to the retainer middle portion.

In many embodiments, the seal includes vent ports, which can be used to selectively distribute applied pressure within

the seal. For example, the inner wall can include a vent port in communication with a first enclosed cell of the enclosed cell areas. And one of the webs can include a vent port in communication with the first enclosed cell area and a second enclosed cell area of the enclosed cell areas, the first and second enclosed cell areas being different.

In many embodiments, the outer wall includes a plurality of recesses extending circumferentially at least partially around the bypass duct. The recesses are configured to accommodate adhesive used to bond the outer wall to a support, such as adhesive used to bond the outer wall to the retainer. The recesses are disposed between non-recessed areas that are substantially aligned with the webs. The non-recessed areas substantially interface with the support, for example, with the retainer middle portion.

In many embodiments, the seal includes a plurality of elongate pull-through features that extend from the outer wall through holes in the retainer middle portion. The pull-through features interface with the holes in the retainer middle portion to position the outer wall relative to the retainer middle portion.

In many embodiments, the inner wall includes an embedded reinforcement layer. The inner wall reinforcement layer increases the stiffness of the inner wall, thereby serving to reduce aerodynamic induced deflections and associated drag when the VAFN is in the deployed position. The embedded reinforcement layer can have a plurality of reduced-stiffness sections distributed circumferentially at least partially around the engine centerline to reduce stiffness of the reinforcement layer circumferential to the engine centerline.

In another aspect, a seal assembly is disclosed for a turbofan engine having a VAFN. The engine includes a forward assembly and the VAFN disposed behind the forward assembly and movable relative to the forward assembly between a stowed position and a deployed position. The forward assembly defines a bypass duct extending circumferentially at least partially around the engine centerline. The bypass duct is configured to transport bypass airflow of the engine. The forward assembly has an aft edge that extends circumferentially at least partially around the bypass duct. An upstream bypass flow exit for the bypass duct is defined between the forward assembly and the VAFN when the VAFN is in the deployed position. An outer surface of the VAFN provides an aerodynamic boundary for bypass airflow exited through the bypass flow exit. The seal assembly includes a seal and a seal retainer attached to the seal. The seal includes an inner wall and a plurality of webs attached to the inner wall and extending transversely therefrom. Each of at least two of the webs is configured to extend circumferentially at least partially around the bypass duct. The inner wall defines an exposed inner surface configured to extend circumferentially at least partially around the bypass duct. The inner surface is configured to provide a substantially smooth aerodynamic boundary for bypass airflow exited through the bypass flow exit when the VAFN is in the deployed position. At least a portion of the inner surface is configured to interface with the VAFN outer surface when the VAFN is in the stowed position so as to seal the bypass flow exit. Each of at least two of the webs is configured to deform into a non-planar configuration when the VAFN is in the stowed position. The seal retainer defines a seal receiving cavity for the seal. The seal receiving cavity has an arcuate shape configured to extend circumferentially at least partially around the bypass duct. The seal retainer includes a retainer forward flange, a retainer aft flange, and a retainer middle portion extending between the retainer forward and aft flanges. Each of the retainer forward and aft flanges is configured to extend circumferentially at least partially

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tially around the bypass duct and be attached to the forward assembly. The seal is configured to be compressed between the VAFN and the retainer middle portion when the VAFN is in the stowed position.

For a fuller understanding of the nature and advantages of the present invention, reference should be made to the ensuing detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view illustration of a turbofan engine that includes a variable area fan nozzle (VAFN) assembly, in accordance with many embodiments.

FIG. 2 is a cross-sectional view of the turbofan engine of FIG. 1.

FIG. 3 is an end view of the turbofan engine of FIG. 1.

FIG. 4 is a perspective view that shows a portion of the VAFN assembly of the turbofan engine of FIG. 1.

FIG. 5 is another perspective view that shows a portion of the VAFN assembly of the turbofan engine of FIG. 1.

FIG. 6 is a cross-sectional view showing a VAFN seal assembly attached to a nacelle forward assembly, in accordance with many embodiments.

FIG. 7 is a cross-sectional view that shows a VAFN main seal being compressed between a VAFN and a VAFN main seal retainer, in accordance with many embodiments.

FIG. 8 is a cross-sectional view that shows the VAFN seal assembly of FIG. 6 when the VAFN is in a deployed position, in accordance with many embodiments.

FIG. 9 is a cross-sectional view illustrating details of the VAFN seal assembly of FIG. 6, in accordance with many embodiments.

FIG. 10 is a rear-view of a VAFN seal assembly attached to a nacelle assembly that illustrates a surface of revolution (SOR) region, transition regions, and flat regions of the VAFN seal assembly, in accordance with many embodiments.

FIG. 11 includes cross-sectional views of a VAFN in a stowed position interfacing with the VAFN seal assembly in one of the flat regions and in the surface of revolution (SOR) region, in accordance with many embodiments.

FIG. 12 is a perspective view showing the VAFN seal assembly of FIG. 10.

FIGS. 13a and 13b are perspective views showing one of the transition regions and one of the flat regions of the VAFN seal assembly of FIG. 10.

FIG. 14 is a perspective view illustrating internal reinforcement layers of the VAFN seal assembly of FIG. 12.

FIG. 15 is a cross-sectional view of the VAFN main seal illustrating adhesive accommodating recesses and associated adjacent non-recessed regions, in accordance with many embodiments.

FIGS. 16a and 16b are perspective views illustrating elongate pull-through features of the VAFN main seal that interface with holes in the seal retainer to accurately position the main seal relative to the seal retainer during bonding of the main seal to the seal retainer, in accordance with many embodiments.

FIG. 17 is a cross-sectional view illustrating the location of vent ports in a VAFN main seal, in accordance with many embodiments.

DETAILED DESCRIPTION

In the following description, various embodiments of the present invention will be described. For purposes of explanation, specific configurations and details are set forth in order to provide a thorough understanding of the embodiments.

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However, it will also be apparent to one skilled in the art that the present invention can be practiced without the specific details. Furthermore, well-known features may be omitted or simplified in order not to obscure the embodiment being described.

Referring now to the drawings, in which like reference numerals represent like parts throughout the several views, FIG. 1 shows a turbofan engine 10 that includes a variable area fan nozzle (VAFN) assembly 12 having a translating fan nozzle 50 that can be selectively adjusted, for example, as the engine 10 operates under different flight conditions. As discussed above, such an adjustment can be used to optimize the engine's performance. As shown in FIG. 2, the translating fan nozzle 50 can be selectively translated (i.e., moved fore and aft) to vary the fan nozzle's exit area 52 and to adjust how much of the bypass airflow exits through an upstream exit 60 formed by the VAFN assembly 12. For example, when the translating fan nozzle 50 is in the stowed position, the upstream exit 60 is closed and the exit area 52 is minimized, thereby maximizing the fan pressure ratio (FPR) for a particular operational condition. And when the translating fan nozzle 50 is in the fully deployed position, the upstream exit 60 opening is maximized and the exit area 52 is maximized, thereby minimizing the FPR for the particular operational condition. Accordingly, selectively positioning the translating fan nozzle 50 can be used to selectively vary the FPR. And varying the FPR can be used to optimize engine performance, increase fan stall margins, avoid engine malfunction, and/or avoid engine shutdown. For purposes of illustration, the VAFN assembly 12 is shown in the context of a turbofan aircraft engine 10. The engine 10 can be mounted to a wing or fuselage of an aircraft, for example, by a pylon or other similar support (not shown in the figures).

The engine 10 includes an engine core 16 and a nacelle 18. The engine core 16 is housed in a core cowl 19. As shown in FIG. 2, a fan 20 is mounted adjacent to an upstream end of the nacelle 18, and includes a series of fan blades 22 that are rotated about the engine centerline CL during engine operation so as to draw a flow of air into an inlet end 26 of the engine 10. An annular bypass duct 24 is defined between the engine core 16 and the nacelle 18. The airflow drawn into the engine 10 is accelerated by the rotating fan blades 22. A portion of the airflow is directed into and through a multi-stage compressor (not illustrated) within the engine core 16. The engine core airflow through the engine core 16 is initially passed through the compressor to increase the airflow pressure, after which the pressurized air is passed through a combustor (not shown), where it is mixed with fuel and the mixture ignited. The combustion of the fuel and air mixture within the combustor causes the air to expand, which in turn drives a series of turbines at the rear of the engine, indicated generally at 38, to rotate and in turn to provide power to the fan 20.

The bypass airflow accelerated by the rotating fan blades 22 passes through the bypass duct 24, past stators 40, and out through the nozzle assembly 12. The fan 20 produces most of the engine thrust. The high pressure heated exhaust gases from the combustion of the fuel and air mixture are directed out of the rear of the engine core 16 downstream of the turbine section 38.

The translating fan nozzle 50 can include a ring-like annular airfoil structure mounted at the trailing end of a thrust reverser 80, adjacent to and circumscribing at least a portion of the engine core cowl 19. The area between the trailing edge of the translating fan nozzle 50 and the core cowl 19 defines the nozzle exit area 52 for the translating fan nozzle 12. As shown in FIG. 1 and FIG. 3, the translating fan nozzle 50 includes an arcuate first ring section 54 and an arcuate second

ring section **56**. Each ring section **54, 56** is axially translatable in the direction of the bidirectional arrow **58**. Translation of the fan nozzle **50** effects a desired size of the upstream exit **60** and varies the outlet geometry and exit area **52** of the fan nozzle **12** outlet for the engine bypass airflow. The fan nozzle **50** can be translated, for example, by a plurality of ring actuators **70**.

The thrust reverser **80** is adjacent to and forward of the translating fan nozzle **50** to block and redirect the bypass airflow in the bypass duct **24** into a thrust reversing vector. In FIG. 1, the thrust reverser **80** and the translating fan nozzle **50** are in stowed (closed) positions. The thrust reverser **80** includes an arcuate first sleeve (cowl) section **82** and an opposed arcuate second sleeve (cowl) section **84** (shown in FIG. 3). The thrust reverser sleeve sections **82, 84** are axially translatable in the direction of the bidirectional arrow **86** by a plurality of sleeve actuators **90**. The thrust reverser sleeve sections **82, 84** are translatable over a series of cascade vanes **88**. The cascade vanes **88** are indicated by dashed lead lines in FIG. 1 because they are not visible when the thrust reverser **80** is in the stowed position. Axial translation of the sleeve sections **82, 84** in the fore and aft directions allows the bypass airflow to be passed through the cascade vanes **88** to generate a thrust-reversing vector.

FIG. 3 is a cross-sectional view of the aft end of the engine **10**, and illustrates the arrangement of the ring and sleeve actuators **70, 90**, respectively, around the periphery of the engine **10**. As shown in FIG. 1, and more clearly in FIG. 3, the sleeve half section **82** and the ring section **54** cooperate to generally define an approximately 180 degree sector of the combined thrust reverser and translating fan nozzle. Likewise, sleeve half section **84** and ring half section **56** cooperate to generally define an opposed approximately 180 degree sector of the thrust reverser and translating fan nozzle. Together, these approximate 180 degree sectors cooperate to define the entire approximate 360 degree thrust reverser and translating fan nozzle.

As shown in FIGS. 1-3, each thrust reverser sleeve half-section **82, 84** of the thrust reverser **80** is translated by one or more (three are shown) peripherally-spaced sleeve actuators **90** fixedly mounted in the nacelle **18**. In the embodiment shown, three actuators **90** are used for each sleeve half-section **82, 84**. Each ring section **54, 56** of the translating fan nozzle **50** similarly is translated by one or more (three are shown) peripherally-spaced ring actuators **70**. Ring actuators **70** can be mounted on an adjacent thrust reverser sleeve section **82, 84**, respectively. The ring actuators **70** can be powered by, for example, electricity, mechanical means, pneumatics, hydraulics, or other suitable means, with appropriate power cables and conduits (not shown) passing via pre-defined passages between or above the thrust reverser cascade boxes or pivot doors. The number and arrangement of ring and sleeve actuators **70, 90** can be varied, for example, according to the thrust reverser and translating fan nozzle configuration, and according to other factors. The ring sections **54, 56** may be mounted in, for example, upper and lower guide structures **102** located at each end of corresponding sleeve sections **82, 84**, respectively. Guide tubes **104** may be mounted in the nacelle **18** and may extend into the ring sections **54, 56** to stabilize the ring sections **54, 56** against undesirable translation and/or vibration. Guide tubes can alternatively be mounted in the thrust reverser **80**.

The translating fan nozzle **50** can be a continuous (e.g., one-piece) or, as shown in FIG. 3, a continuing (e.g., split or multi-section) generally annular ring having an airfoil cross section. Accordingly, the upstream exit **60** (formed when the translating fan nozzle **50** moves in the aft direction away from

the sleeve sections **82, 84**) can have the form of a generally annular gap extending around the perimeter of the rear of the nacelle **18**. Other outlet shapes can also be used, for example, oval, etc. The generally annular gap between the ring sections **54, 56** and the sleeve sections **82, 84** can be continuous, for example, or interrupted at one or more locations, such as, for example, at points of bifurcation or other separation of the translating fan nozzle **50**. The bypass duct **24** may also be interrupted at one or more locations.

The translating fan nozzle **50** and surrounding structure are described below with reference to FIG. 4 and FIG. 5. In FIG. 4 and FIG. 5, elements that are obscured or partially obscured due to intervening elements are indicated by dashed lead lines.

FIG. 4 is a partial view of the mounting structure for a first ring section **54** of the translating fan nozzle **50** and the corresponding, adjacent first sleeve section **82** of the thrust reverser **80**. The second ring section **56** of the translating fan nozzle **50** and the second sleeve section **84** of the thrust reverser **80**, which are shown in FIG. 1 and FIG. 3, can be mounted in a similar manner. In FIG. 4, the thrust reverser **80** is in a stowed position, covering the cascade vanes **88**. The translating fan nozzle **50** is in an open or deployed position so that an upstream exit **60** is defined between the first ring section **54** and the first sleeve section **84**. The rearward axial translation of the first ring section **54** to the deployed position is indicated by the arrow A. The ring actuators **70** can extend from the sleeve section **82**, across the upstream exit **60**, and connect to a fore end of the ring section **54**. The guide tubes **104** can also extend from the sleeve section **82**, across the upstream exit **60**, and connect to the fore end of the ring section **54**. A sleeve actuation cable **96** can connect to each sleeve actuator **90** to provide simultaneous actuation of each actuator **90**.

FIG. 5 shows the thrust reverser **80** in a deployed position and the translating fan nozzle **50** in the open position. The rearward axial translation of the first sleeve section **82** from the position shown in FIG. 4 to the deployed position is indicated by the arrow B. Rearward translation of the sleeve section **82** exposes the cascade vanes **88** during operation of the thrust reverser **80**. The ring section **54** can also be translated aft during operation of the thrust reverser **80**, as shown in this embodiment. Translation of the ring section **54** at the same time that the thrust reverser **80** is deployed, may be optional because the bypass flow is rerouted through the cascade vanes **88**.

VAFN Seal Assembly

FIG. 6 shows a cross section of a VAFN seal assembly **200** attached to a nacelle assembly **202**, in accordance with many embodiments. The VAFN seal assembly **200** includes a main seal **204** and a main seal retainer **206**. The main seal **204** includes an inner wall **208**, an outer wall **210**, four webs **212**, a main seal forward flange **214**, and a main seal aft flange **216**, all of which extend circumferentially at least partially around the bypass duct, for example, for at least 90 degrees around the bypass duct. The inner wall **208** defines an exposed inner surface **218** that provides a substantially smooth aerodynamic boundary for bypass airflow exited through the bypass flow exit when the VAFN is in the deployed position. The inner wall **208**, webs **212**, and the outer wall **210** define four enclosed cell areas **220**. The outer wall **210** is secured and/or attached to the main seal retainer **206**, for example, by adhesive bonding.

The main seal retainer **206** includes a retainer forward flange **222**, a retainer aft flange **224**, and a retainer middle portion **226** extending between the retainer forward flange **222** and the retainer aft flange **224**. A circumferentially

extending row of nut plates **228** is attached to the retainer forward flange **222** for receiving a corresponding row of removable fasteners **229** used to attach the forward end of the VAFN seal assembly **200** to a flange **230** of the nacelle assembly **202**. And a circumferentially extending row of nut plates **232** is attached to the retainer aft flange **224** for receiving a corresponding row of removable fasteners (not shown) used to attach the aft end of the VAFN seal assembly **200** to an outer panel **234** of the nacelle assembly **202**. The seal forward flange **214** is clamped between the retainer forward flange **222** and the nacelle assembly flange **230**. The seal aft flange **216** is also clamped between the nacelle assembly outer panel **234** and the retainer aft flange **224**. The combination of the seal retainer **206** and the nacelle assembly outer panel **234** provides support structure for the main seal **204** that accurately positions the main seal **204** and reacts loads from the main seal **204** into the nacelle assembly **202**. The seal retainer **206** is configured to provide a seal receiving cavity that accommodates the main seal **204**. And the circumferential attachment of the seal retainer **206** to the nacelle assembly **202** provides a combined structure that accurately positions the seal receiving cavity relative to the VAFN.

In the embodiment shown, each of the webs **212** has a constant thickness planar configuration. While constant thickness planar webs **212** are shown, any suitable alternate web configuration can be used. For example, webs having varying thickness and/or non-planar webs can be used.

FIG. 7 shows a cross section of the main seal **204** being compressed between a stowed position VAFN ring section **54** and the main seal retainer **206**. In the stowed position, the relatively stiff VAFN ring section **54** deflects the inner surface **218** toward the outer wall **210**, thereby deforming the inner wall **208** and significantly deforming the four webs **212** such that each of the webs **212** is resiliently deformed into a non-planar configuration, thereby creating 'lines of sealing' between the main seal **204** and the VAFN ring section **54**. Although each of the webs **212** is resiliently deformed into a non-planar configuration in the embodiment described, other embodiments having one or more webs that are not deformed into a non-planar configuration are possible. In the embodiment shown, the webs **212** are not aligned in the same direction the inner wall **208** is deflected, thereby producing eccentric loading on the webs **212**. Such eccentric loading reduces the force required to drive the webs **212** into the post-buckled non-planar configuration shown. In many embodiments, the main seal **204** is primarily formed from a reinforced elastomeric material with suitable resiliency so that the main seal **204** is not permanently deformed as a result of the deformation imposed by the stowed VAFN ring section **54**.

The main seal **204** can be fabricated from a suitable material. For example, the main seal **204** can be fabricated from Silicon Rubber per Aerospace Materials Specification (AMS) **3346** with polyester fabric on the surface.

FIG. 8 shows the nacelle assembly **202** and the VAFN seal assembly **200** relative to the VAFN ring section **54** in a deployed position. When the VAFN ring section **54** is in a deployed position, a bypass flow exit **236** is formed between the combination of the nacelle assembly **202** and the VAFN seal assembly **200** and the VAFN ring section **54**. As shown, the inner surface **218** of the main seal **204** provides an aerodynamic boundary for an airflow **238** that exits through the bypass flow exit **236**.

When the VAFN ring section **54** is in a deployed position, the main seal **204** is subjected to applied pressure loading. The main seal **204** is designed to react the applied pressure loading without experiencing deflections that would produce excessive levels of aerodynamic drag. For example, the planar webs **212** support the inner wall **208** at multiple locations along the inner wall **208**, thereby helping to maintain the position and the shape of the inner wall **208**. The combined structure provided by the nacelle assembly outer panel **234** and the main seal retainer **206** provides a hard trailing edge **240**, which experiences little or no significant levels of deflection relative to adjacent forward portions of the nacelle assembly **202**. And the combined structure provided by the nacelle assembly outer panel **234** and the main seal retainer **206** accurately supports the main seal **204** and reacts loads from the main seal **204** without experiencing significant levels of deflection relative to adjacent forward portions of the nacelle assembly **202**.

FIG. 9 shows additional details of the VAFN seal assembly **200**. The main seal **204** includes an embedded surface reinforcement **242** that stiffens at least an aft portion of the inner wall **208**, an embedded aft attach reinforcement **244** that reinforces the main seal aft flange **216**, and an embedded forward attach reinforcement **246** that reinforces the main seal forward flange **214**. The embedded surface reinforcement **242** can be made from any suitable rigid material, for example, a cured composite laminate such as a fiberglass laminate. The embedded surface reinforcement **242** can be configured to stiffen the inner wall in the fore and aft direction and can include features (e.g., circumferentially distributed reduced cross-sectional areas) that reduce the amount of stiffness added to the main seal **204** in the circumferential direction so as to reduce the amount of additional circumferential hoop loading associated with circumferential deflection of the embedded surface reinforcement **242** that results from radial deflection of the inner wall **208** when the VAFN ring section **54** is in the stowed position. The aft attach reinforcement **244** and the forward attach reinforcement **246** can be made from a suitable material, for example, a sheet of corrosion resistant steel of suitable thickness. The main seal retainer **206** can be made from a suitable material (e.g., sheet metal, a composite laminate). For example, the main seal retainer **206** can be made from a graphite epoxy laminate. The main seal **204** can include a "no strike-through" surface fabric **248** on the seal inner wall **208** for durability and low friction between the VAFN ring section **54** and the inner wall **208**. The main seal **204** can be bonded and/or mechanically retained to the main seal retainer **206** along the outer wall **210**. Alternatively, a durable and low friction material may be used as the main seal **204** or be integrally fabricated into the main seal **204**.

FIG. 10 is a rear-view of the VAFN seal assembly **200** attached to the nacelle assembly **202**. The VAFN seal assembly **200** includes a surface of revolution (SOR) region **250**, transition regions **252**, and flat regions **254**. Throughout the SOR region **250**, the main seal **204** has a constant cross section (as shown in FIG. 9) and is axially symmetric relative to the engine centerline. In the transition regions, the depth of the main seal **204** is reduced from the full cross section of the SOR region **250** down to just the inner wall **208** near the start of the corresponding flat region **254**. For example, the main seal **204** can be initially formed with the full cross section of the SOR region **250** extended through the transition regions **252** and then the portions of the main seal **204** and the webs **212** in the transition regions **252** can be tapered in height until only the inner wall **208** remains. FIG. 11 includes cross-sectional views of the VAFN ring section **54** in the stowed position interfacing with the VAFN seal assembly **200** in one of the flat regions **254** and in the surface of revolution (SOR) region **250** (deflection of the main seal **204** not depicted).

FIG. 12 is a perspective view showing the VAFN seal assembly **200** detached from the nacelle assembly **202**. The

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seal assembly includes the main seal **204** that spans the SOR region **250** and the transition regions **252**, and optionally, a bulb seal **256** at each end flat region **254**; bulb seals can be used if the aerodynamic loft lines are such that the main seal **204** is unable to provide, by itself, adequate sealing in these areas.

FIGS. **13a** and **13b** are perspective views showing one of the transition regions and one of the flat regions of the VAFN seal assembly **200**. A transition region portion **258** of the main seal retainer **206** is shaped to interface with the trimmed shape of the main seal **204** in the transition region **252**. A hoop retainer **260** is used at each end of the main seal **204** and a bulb seal retainer **262** is used to retain each of the bulb seals **256**.

FIG. **14** is a perspective view illustrating the internal reinforcement layers of the main seal **204** with the elastomeric body of the main seal **204** not shown for clarity. As illustrated, the embedded surface reinforcement **242** extends circumferentially and has circumferentially-spaced reduced-stiffness sections **264** (e.g., trim-outs, locations between discrete disconnected sections), which serve to reduced the stiffness in the circumferential direction that is added to the main seal **204** by the embedded surface reinforcement **242**. In contrast, each of the aft attach reinforcement **244** and the forward attach reinforcement **246** has a constant cross section in the circumferential direction. The aft attach reinforcement **244** and the forward attach reinforcement **246** are not subjected to any significant radial deflection when the VAFN ring section **54** is in the stowed position (as illustrated in FIG. **7**). Accordingly, circumferential hoop loads are not significantly impacted by the circumferential stiffness added by the aft and forward attach reinforcements **244**, **246**.

FIG. **15** is a cross-sectional view illustrating adhesive accommodating recesses **266** in the main seal **204** and associated adjacent non-recessed regions **268**. The recesses **266** extend circumferentially along the circumferential length of the main seal **204** and accommodate adhesive used to bond the outer wall **210** to the main seal retainer **206**. The recesses **266** are disposed between and adjacent to the non-recessed regions **268**, which are aligned with the webs **212**. As shown, the non-recessed regions **268** interface with the main seal retainer **206**, thereby accurately positioning the main seal **204** relative to the main seal retainer **206**.

FIGS. **16a** and **16b** are perspective views illustrating elongate pull-through features **270** of the main seal **204**. The pull-through features **270** interface with holes in the main seal retainer **206** (partially removed to enhance clarity) to accurately position the main seal **204** relative to the main seal retainer **206** during bonding of the main seal **204** to the main seal retainer **206**. The pull-through features **270** are integrally formed parts of the main seal **204**. The pull-through features **270** include a lower cylindrical portion **272** and an upper cylindrical portion **274**. Each of the lower cylindrical portions **272** has a diameter selected to be suitably larger than a diameter of the corresponding hole in the main seal retainer **206** so that a suitable amount of interference fit is generated between the lower cylindrical portion **272** and the hole when installed. Each of the upper cylindrical portions **274** has a diameter that is smaller than the diameter of the corresponding hole in the main seal retainer **206** so that the upper cylindrical portion **274** can be freely inserted into the corresponding hole during the installation process. Following insertion of the upper cylindrical portions **274** into the holes of the main seal retainer **206**, each of the pull-through features **270** is pulled relative to the main seal retainer **206** to pull the lower cylindrical portion **272** through the hole. When the pull-through feature **270** is pulled, the diameter of the lower cylindrical portion **272** reduces temporarily in response to the axial strain

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imposed on the lower cylindrical portion **272**, thereby allowing the lower cylindrical portion **272** to be pulled partially through the corresponding hole. Upon release of the pull-through feature **270**, the lower cylindrical portion **272** expands back to the original diameter, thereby engaging the hole and serving to retain the main seal **204** relative to the main seal retainer **206**. The pull-through features **270** are distributed along the main seal **204**. Many of the pull-through features **270** are aligned with the non-recessed areas **268**, thereby providing multiple locations along the main seal **204** where the pull-through features **270** serve to ensure contact between the non-recessed areas **268** and the main seal retainer **206** so as to accurately position the main seal **204** relative to the main seal retainer **206** during the bonding of the main seal **204** to the main seal retainer **206**. The protruding portions of the pull-through features **270** can be cut off after installation to reduce weight.

FIG. **17** is a cross-sectional view illustrating the location of vent ports **276**, **278**, **280** in the VAFN main seal **204**, in accordance with many embodiments. The inner wall **208** includes a first vent port **276** that places a first enclosed cell area **282** of the main seal **204** in communication with the bypass duct. Web vent ports **278** place the first enclosed cell area **282** in communication with a second enclosed cell area **284**, a third enclosed cell area **286**, and a fourth enclosed cell area **288**. Accordingly, on account of the first vent port **276** and the web vent ports **278**, the pressure differential across the inner wall **208** in the forward portion of the main seal **204** is reduced, which serves to reduce associated deflections of the inner wall **208**. Instead, the pressure differential is transferred to the outer wall **210**, which directly transfers the associated loads to the main seal retainer **206**. An exterior vent port **280** vents an aft cavity **290** through the nacelle assembly outer panel **234**.

Other variations are within the spirit of the present invention. Thus, while the invention is susceptible to various modifications and alternative constructions, certain illustrated embodiments thereof are shown in the drawings and have been described above in detail. It should be understood, however, that there is no intention to limit the invention to the specific form or forms disclosed, but on the contrary, the intention is to cover all modifications, alternative constructions, and equivalents falling within the spirit and scope of the invention, as defined in the appended claims.

The use of the terms "a" and "an" and "the" and similar referents in the context of describing the invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms "comprising," "having," "including," and "containing" are to be construed as open-ended terms (i.e., meaning "including, but not limited to,") unless otherwise noted. The term "connected" is to be construed as partly or wholly contained within, attached to, or joined together, even if there is something intervening. Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided herein, is intended merely to better illuminate embodiments of the invention and does not pose a limitation on the scope of the invention unless otherwise claimed. No

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language in the specification should be construed as indicating any non-claimed element as essential to the practice of the invention.

Preferred embodiments of this invention are described herein, including the best mode known to the inventors for carrying out the invention. Variations of those preferred embodiments may become apparent to those of ordinary skill in the art upon reading the foregoing description. The inventors expect skilled artisans to employ such variations as appropriate, and the inventors intend for the invention to be practiced otherwise than as specifically described herein. Accordingly, this invention includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the invention unless otherwise indicated herein or otherwise clearly contradicted by context.

All references, including publications, patent applications, and patents, cited herein are hereby incorporated by reference to the same extent as if each reference were individually and specifically indicated to be incorporated by reference and were set forth in its entirety herein.

What is claimed is:

1. A nacelle for a turbofan engine having an engine centerline, the nacelle comprising:

a forward assembly that defines a bypass duct extending circumferentially at least partially around the engine centerline, the bypass duct being configured to transport bypass airflow of the engine, the forward assembly having an aft edge that extends circumferentially at least partially around the bypass duct;

a variable area fan nozzle (VAFN) disposed behind the forward assembly and movable relative to the forward assembly between a stowed position and a deployed position, an upstream bypass flow exit for the bypass duct being defined between the forward assembly and the VAFN when the VAFN is in the deployed position, an outer surface of the VAFN providing an aerodynamic boundary for bypass airflow exited through the bypass flow exit; and

a seal attached to the forward assembly, the seal including an inner wall and a plurality of webs attached to the inner wall and extending transversely therefrom, each of the webs extending circumferentially at least partially around the bypass duct, the inner wall defining an exposed inner surface that extends circumferentially at least partially around the bypass duct, the inner surface providing a substantially smooth aerodynamic boundary for bypass airflow exited through the bypass flow exit when the VAFN is in the deployed position, at least a portion of the inner surface interfacing with the VAFN outer surface when the VAFN is in the stowed position, at least one of the plurality of webs deformable into a non-planar configuration when the VAFN is in the stowed position.

2. The nacelle of claim 1, wherein the seal extends circumferentially around the engine centerline for at least 90 degrees.

3. The nacelle of claim 2, wherein a height of the seal is tapered down near an end of the seal.

4. The nacelle of claim 3, further comprising a bulb seal attached to the forward assembly and disposed at the end of the seal, the bulb seal being compressed between the forward assembly and the VAFN when the VAFN is in the stowed position.

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5. The nacelle of claim 1, wherein each of the webs has a planar configuration when the VAFN is in the deployed position.

6. The nacelle of claim 1, wherein the seal includes an elastomeric material.

7. The nacelle of claim 1, wherein the elastomeric material includes silicon rubber.

8. The nacelle of claim 1, further comprising a seal retainer defining a seal receiving cavity for the seal; the seal receiving cavity having an arcuate shape extending circumferentially at least partially around the bypass duct; the seal retainer includes a retainer forward flange, a retainer aft flange, and a retainer middle portion extending between the retainer forward and aft flanges; each of the retainer forward and aft flanges extending circumferentially at least partially around the bypass duct and being attached to the forward assembly; the seal located between the VAFN and the retainer middle portion when the VAFN is in the stowed position.

9. The nacelle of claim 8, wherein the seal includes a seal forward flange that extends circumferentially at least partially around the bypass duct and a seal aft flange that extends circumferentially at least partially around the bypass duct, the seal forward flange being disposed between the retainer forward flange and the forward assembly, the seal aft flange being disposed between the retainer aft flange and the forward assembly.

10. The nacelle of claim 9, wherein at least one of the seal forward flange or the seal aft flange includes an embedded reinforcement layer.

11. The nacelle of claim 10, wherein:

the seal forward flange includes an embedded reinforcement layer;

the seal aft flange includes an embedded reinforcement layer; and

the inner wall includes an embedded reinforcement layer.

12. The nacelle of claim 11, wherein the inner wall reinforcement layer has a plurality of reduced-stiffness sections distributed circumferentially at least partially around the engine centerline to reduce stiffness of the inner wall reinforcement layer circumferential to the engine centerline.

13. The nacelle of claim 8, wherein the seal includes an outer wall offset from the inner wall and attached to the webs, a plurality of enclosed cell areas being defined within the seal and extending circumferentially at least partially around the bypass duct, the outer wall being attached to the retainer middle portion.

14. The nacelle of claim 13, wherein:

the inner wall includes a vent port in communication with a first enclosed cell area of the enclosed cell areas; and one of the webs includes a vent port in communication with the first enclosed cell area and a second enclosed cell area of the enclosed cell areas, the first and second enclosed cell areas being different.

15. The nacelle of claim 13, wherein the outer wall is bonded to the retainer middle portion.

16. The nacelle of claim 15, wherein the outer wall includes a plurality of recesses extending circumferentially at least partially around the bypass duct, the recesses accommodating adhesive used to bond the outer wall to the retainer, the recesses being disposed between non-recessed areas substantially aligned with the webs, the non-recessed areas substantially interfacing with the retainer middle portion.

17. The nacelle of claim 16, wherein the seal includes a plurality of elongate pull-through features extending from the outer wall through holes in the retainer middle portion, the

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pull-through features interfacing with the holes in the retainer middle portion to position the outer wall relative to the retainer middle portion.

18. The nacelle of claim 1, wherein the inner wall includes an embedded reinforcement layer.

19. The nacelle of claim 18, wherein the inner wall reinforcement layer has a plurality of reduced-stiffness sections distributed circumferentially at least partially around the engine centerline to reduce stiffness of the reinforcement layer circumferential to the engine centerline.

20. A seal assembly for a turbofan engine, the engine including a forward assembly and a VAFN disposed behind the forward assembly and movable relative to the forward assembly between a stowed position and a deployed position, the forward assembly defining a bypass duct extending circumferentially at least partially around the engine centerline, the bypass duct being configured to transport bypass airflow of the engine, the forward assembly having an aft edge that extends circumferentially at least partially around the bypass duct, an upstream bypass flow exit for the bypass duct being defined between the forward assembly and the VAFN when the VAFN is in the deployed position, an outer surface of the VAFN providing an aerodynamic boundary for bypass airflow exited through the bypass flow exit, the seal assembly including:

- a seal including an inner wall and a plurality of webs attached to the inner wall and extending transversely there-from, each of at least two of the webs configured to

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extend circumferentially at least partially around the bypass duct, the inner wall defining an exposed inner surface configured to extend circumferentially at least partially around the bypass duct, the inner surface configured to provide a substantially smooth aerodynamic boundary for bypass airflow exited through the bypass flow exit when the VAFN is in the deployed position, at least a portion of the inner surface configured to interface with the VAFN outer surface when the VAFN is in the stowed position so as to seal the bypass flow exit, each of at least two of the webs being configured to deform into a non-planar configuration when the VAFN is in the stowed position; and

- a seal retainer attached to the seal and defining a seal receiving cavity for the seal; the seal receiving cavity having an arcuate shape configured to extend circumferentially at least partially around the bypass duct; the seal retainer includes a retainer forward flange, a retainer aft flange, and a retainer middle portion extending between the retainer forward and aft flanges; each of the retainer forward and aft flanges configured to extend circumferentially at least partially around the bypass duct and be attached to the forward assembly; the seal being configured to be compressed between the VAFN and the retainer middle portion when the VAFN is in the stowed position.

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